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# Measurement of the Branching Ratio
## $\Gamma(D_s^{*+} \to D_s^+ \pi^0)/\Gamma(D_s^{*+} \to D_s^+ \gamma)$

The *BABAR* Collaboration

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## Abstract

The $(\Delta I = 1)$ decay $D_s^{*+} \to D_s^+ \pi^0$ and $(\Delta I = 0)$ decay $D_s^{*+} \to D_s^+ \gamma$ have been reconstructed using 90.4 fb$^{-1}$ of data recorded by the *BABAR* detector at the PEP-II asymmetric-energy $e^+e^-$ collider. The relative branching fraction of isospin violating decay to isospin conserving decay has been measured. Our preliminary result for this ratio is $\Gamma(D_s^{*+} \to D_s^+ \pi^0)/\Gamma(D_s^{*+} \to D_s^+ \gamma) = 0.0621 \pm 0.0049$ (stat) $\pm 0.0063$ (syst). In addition we reconstruct the decays $D^{*0} \to D^0 \pi^0$ and $D^{*0} \to D^0 \gamma$ for completeness and measure a preliminary relative branching fraction to be $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma) = 1.740 \pm 0.020$(stat) $\pm 0.125$(syst). Both measurements represent significant improvements over present world averages.

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The *BABAR* Collaboration,

B. Aubert, R. Barate, D. Boutigny, F. Couderc, J.-M. Gaillard, A. Hicheur, Y. Karyotakis, J. P. Lees,
V. Tisserand, A. Zghiche

*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*

A. Palano, A. Pompili

*Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy*

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

*Institute of High Energy Physics, Beijing 100039, China*

G. Eigen, I. Ofte, B. Stugu

*University of Bergen, Inst. of Physics, N-5007 Bergen, Norway*

G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles,
C. T. Day, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth,
Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein,
N. A. Roe, M. T. Ronan, V. G. Shelkov, W. A. Wenzel

*Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA*

M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson

*University of Birmingham, Birmingham, B15 2TT, United Kingdom*

M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, M. Steinke

*Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany*

J. T. Boyd, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. E. Latham, F. F. Wilson

*University of Bristol, Bristol BS8 1TL, United Kingdom*

T. Cuhadar-Donszelmann, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna, D. Thiessen

*University of British Columbia, Vancouver, BC, Canada V6T 1Z1*

A. Khan, P. Kyberd, L. Teodorescu

*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*

A. E. Blinov, V. E. Blinov, V. P. Druzhinin, V. B. Golubev, V. N. Ivanchenko, E. A. Kravchenko,
A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov

*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*

D. Best, M. Bruinsma, M. Chao, I. Eschrich, D. Kirkby, A. J. Lankford, M. Mandelkern, R. K. Mommsen,
W. Roethel, D. P. Stoker

*University of California at Irvine, Irvine, CA 92697, USA*

C. Buchanan, B. L. Hartfiel

*University of California at Los Angeles, Los Angeles, CA 90024, USA*

S. D. Foulkes, J. W. Gary, B. C. Shen, K. Wang

*University of California at Riverside, Riverside, CA 92521, USA*

D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, Sh. Rahatlou, V. Sharma

*University of California at San Diego, La Jolla, CA 92093, USA*

J. W. Berryhill, C. Campagnari, B. Dahmes, O. Long, A. Lu, M. A. Mazur, J. D. Richman, W. Verkerke

*University of California at Santa Barbara, Santa Barbara, CA 93106, USA*

T. W. Beck, A. M. Eisner, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk,
B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson

*University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA*

J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenko,
F. C. Porter, A. Ryd, A. Samuel, S. Yang

*California Institute of Technology, Pasadena, CA 91125, USA*

S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff

*University of Cincinnati, Cincinnati, OH 45221, USA*

T. Abe, F. Blanc, P. Bloom, S. Chen, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, J. G. Smith,
J. Zhang, L. Zhang

*University of Colorado, Boulder, CO 80309, USA*

A. Chen, J. L. Harton, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng

*Colorado State University, Fort Collins, CO 80523, USA*

D. Altenburg, T. Brandt, J. Brose, M. Dickopp, E. Feltresi, A. Hauke, H. M. Lacker, R. Müller-Pfefferkorn,
R. Nogowski, S. Otto, A. Petzold, J. Schubert, K. R. Schubert, R. Schwierz, B. Spaan, J. E. Sundermann

*Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany*

D. Bernard, G. R. Bonneaud, F. Brochard, P. Grenier, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verderi

*Ecole Polytechnique, LLR, F-91128 Palaiseau, France*

D. J. Bard, P. J. Clark, D. Lavin, F. Muheim, S. Playfer, Y. Xie

*University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*

M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini,
L. Piemontese, A. Sarti

*Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy*

E. Treadwell

*Florida A&M University, Tallahassee, FL 32307, USA*

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi,
M. Piccolo, A. Zallo

*Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy*

A. Buzzo, R. Capra, R. Contri, G. Crosetti, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio,
C. Patrignani, E. Robutti, A. Santroni, S. Tosi

*Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy*

S. Bailey, G. Brandenburg, K. S. Chaisanguanthum, M. Morii, E. Won

*Harvard University, Cambridge, MA 02138, USA*

3

R. S. Dubitzky, U. Langenegger

*Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany*

W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor

*Imperial College London, London, SW7 2AZ, United Kingdom*

M. J. Charles, G. J. Grenier, U. Mallik

*University of Iowa, Iowa City, IA 52242, USA*

J. Cochran, H. B. Crawley, J. Lamsa, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, J. Yi

*Iowa State University, Ames, IA 50011-3160, USA*

M. Biasini, R. Covarelli, M. Pioppi

*Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy*

M. Davier, X. Giroux, G. Grosdidier, A. Höcker, S. Laplace, F. Le Diberder, V. Lepeltier, A. M. Lutz, T. C. Petersen, S. Plaszczynski, M. H. Schune, L. Tantot, G. Wormser

*Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France*

C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright

*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

A. J. Bevan, C. A. Chavez, J. P. Coleman, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, D. E. Hutchcroft, R. J. Parry, D. J. Payne, R. J. Sloane, C. Touramanis

*University of Liverpool, Liverpool L69 72E, United Kingdom*

J. J. Back,[1] C. M. Cormack, P. F. Harrison,[1] F. Di Lodovico, G. B. Mohanty[1]

*Queen Mary, University of London, E1 4NS, United Kingdom*

C. L. Brown, G. Cowan, R. L. Flack, H. U. Flaecher, M. G. Green, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, M. A. Winter

*University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom*

D. Brown, C. L. Davis

*University of Louisville, Louisville, KY 40292, USA*

J. Allison, N. R. Barlow, R. J. Barlow, P. A. Hart, M. C. Hodgkinson, G. D. Lafferty, A. J. Lyon, J. C. Williams

*University of Manchester, Manchester M13 9PL, United Kingdom*

A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lae, V. Lillard, D. A. Roberts

*University of Maryland, College Park, MD 20742, USA*

G. Blaylock, C. Dallapiccola, K. T. Flood, S. S. Hertzbach, R. Kofler, V. B. Koptchev, T. B. Moore, S. Saremi, H. Staengle, S. Willocq

*University of Massachusetts, Amherst, MA 01003, USA*

---

[1]Now at Department of Physics, University of Warwick, Coventry, United Kingdom

R. Cowan, G. Sciolla, S. J. Sekula, F. Taylor, R. K. Yamamoto

*Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA*

D. J. J. Mangeol, P. M. Patel, S. H. Robertson

*McGill University, Montréal, QC, Canada H3A 2T8*

A. Lazzaro, V. Lombardo, F. Palombo

*Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy*

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, J. Reidy, D. A. Sanders, D. J. Summers, H. W. Zhao

*University of Mississippi, University, MS 38677, USA*

S. Brunet, D. Côté, P. Taras

*Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7*

H. Nicholson

*Mount Holyoke College, South Hadley, MA 01075, USA*

N. Cavallo,[2] F. Fabozzi,[2] C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca

*Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy*

M. Baak, H. Bulten, G. Raven, H. L. Snoek, L. Wilden

*NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands*

C. P. Jessop, J. M. LoSecco

*University of Notre Dame, Notre Dame, IN 46556, USA*

T. Allmendinger, K. K. Gan, K. Honscheid, D. Hufnagel, H. Kagan, R. Kass, T. Pulliam, A. M. Rahimi, R. Ter-Antonyan, Q. K. Wong

*Ohio State University, Columbus, OH 43210, USA*

J. Brau, R. Frey, O. Igonkina, C. T. Potter, N. B. Sinev, D. Strom, E. Torrence

*University of Oregon, Eugene, OR 97403, USA*

F. Colecchia, A. Dorigo, F. Galeazzi, M. Margoni, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, G. Tiozzo, C. Voci

*Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy*

M. Benayoun, H. Briand, J. Chauveau, P. David, Ch. de la Vaissière, L. Del Buono, O. Hamon, M. J. J. John, Ph. Leruste, J. Malcles, J. Ocariz, M. Pivk, L. Roos, S. T'Jampens, G. Therin

*Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France*

P. F. Manfredi, V. Re

*Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy*

---

[2]Also with Università della Basilicata, Potenza, Italy

P. K. Behera, L. Gladney, Q. H. Guo, J. Panetta

*University of Pennsylvania, Philadelphia, PA 19104, USA*

C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, F. Bucci, G. Calderini, M. Carpinelli, F. Forti,
M. A. Giorgi, A. Lusiani, G. Marchiori, F. Martinez-Vidal,[3] M. Morganti, N. Neri, E. Paoloni, M. Rama,
G. Rizzo, F. Sandrelli, J. Walsh

*Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy*

M. Haire, D. Judd, K. Paick, D. E. Wagoner

*Prairie View A&M University, Prairie View, TX 77446, USA*

N. Danielson, P. Elmer, Y. P. Lau, C. Lu, V. Miftakov, J. Olsen, A. J. S. Smith, A. V. Telnov

*Princeton University, Princeton, NJ 08544, USA*

F. Bellini, G. Cavoto,[4] R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni,
S. Morganti, M. Pierini, G. Piredda, F. Safai Tehrani, C. Voena

*Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy*

S. Christ, G. Wagner, R. Waldi

*Universität Rostock, D-18051 Rostock, Germany*

T. Adye, N. De Groot, B. Franek, N. I. Geddes, G. P. Gopal, E. O. Olaiya

*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*

R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, P.-F. Giraud, G. Hamel de Monchenault, W. Kozanecki,
M. Legendre, G. W. London, B. Mayer, G. Schott, G. Vasseur, Ch. Yèche, M. Zito

*DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France*

M. V. Purohit, A. W. Weidemann, J. R. Wilson, F. X. Yumiceva

*University of South Carolina, Columbia, SC 29208, USA*

D. Aston, R. Bartoldus, N. Berger, A. M. Boyarski, O. L. Buchmueller, R. Claus, M. R. Convery,
M. Cristinziani, G. De Nardo, D. Dong, J. Dorfan, D. Dujmic, W. Dunwoodie, E. E. Elsen, S. Fan,
R. C. Field, T. Glanzman, S. J. Gowdy, T. Hadig, V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes,
M. H. Kelsey, P. Kim, M. L. Kocian, D. W. G. S. Leith, J. Libby, S. Luitz, V. Luth, H. L. Lynch,
H. Marsiske, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, S. Petrak,
B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, G. Simi, A. Snyder, A. Soha,
J. Stelzer, D. Su, M. K. Sullivan, J. Va'vra, S. R. Wagner, M. Weaver, A. J. R. Weinstein,
W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, C. C. Young

*Stanford Linear Accelerator Center, Stanford, CA 94309, USA*

P. R. Burchat, A. J. Edwards, T. I. Meyer, B. A. Petersen, C. Roat

*Stanford University, Stanford, CA 94305-4060, USA*

S. Ahmed, M. S. Alam, J. A. Ernst, M. A. Saeed, M. Saleem, F. R. Wappler

*State University of New York, Albany, NY 12222, USA*

---

[3]Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain
[4]Also with Princeton University, Princeton, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier

*University of Tennessee, Knoxville, TN 37996, USA*

R. Eckmann, H. Kim, J. L. Ritchie, A. Satpathy, R. F. Schwitters

*University of Texas at Austin, Austin, TX 78712, USA*

J. M. Izen, I. Kitayama, X. C. Lou, S. Ye

*University of Texas at Dallas, Richardson, TX 75083, USA*

F. Bianchi, M. Bona, F. Gallo, D. Gamba

*Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy*

L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, S. Grancagnolo, L. Lanceri, P. Poropat,[5]
L. Vitale, G. Vuagnin

*Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy*

R. S. Panvini

*Vanderbilt University, Nashville, TN 37235, USA*

Sw. Banerjee, C. M. Brown, D. Fortin, P. D. Jackson, R. Kowalewski, J. M. Roney, R. J. Sobie

*University of Victoria, Victoria, BC, Canada V8W 3P6*

H. R. Band, B. Cheng, S. Dasu, M. Datta, A. M. Eichenbaum, M. Graham, J. J. Hollar, J. R. Johnson,
P. E. Kutter, H. Li, R. Liu, A. Mihalyi, A. K. Mohapatra, Y. Pan, R. Prepost, P. Tan, J. H. von
Wimmersperg-Toeller, J. Wu, S. L. Wu, Z. Yu

*University of Wisconsin, Madison, WI 53706, USA*

M. G. Greene, H. Neal

*Yale University, New Haven, CT 06511, USA*

---

[5]Deceased

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The hadronic decay[6] $D_s^{*+} \to D_s^+\pi^0$ violates isospin conservation and should be suppressed with respect to the radiative decay $D_s^{*+} \to D_s^+\gamma$. Cho and Wise [1] have calculated the decay rate for $D_s^{*+} \to D_s^+\pi^0$ using chiral perturbation theory; they describe the process as an isospin conserving decay $D_s^{*+} \to D_s^+\eta$ followed by the conversion of the virtual $\eta$ meson into a $\pi^0$ meson through mixing. The radiative process $D_s^{*+} \to D_s^+\gamma$ proceeds via magnetic transitions to which both the coupling to the charm quark and the light quark contribute. Since a neutral pion or kaon do not couple to the photon, only virtual states with a charged pion or kaon contribute to one-loop corrections of the magnetic moments. The difference in the kaon and pion masses naturally leads to SU(3) flavor-symmetry breaking.

A previous measurement of the ratio $\Gamma(D_s^{*+} \to D_s^+\pi^0)/\Gamma(D_s^{*+} \to D_s^+\gamma)$ by the CLEO Collaboration obtained a result of $0.062\,^{+\,0.020}_{-\,0.018}(\text{stat}) \pm 0.022(\text{syst})$ using $14.7\,^{+\,4.6}_{-\,4.0}$ $D_s^{*+} \to D_s^+\pi^0$ events [2].

The analysis we present here, using $90.4\,\text{fb}^{-1}$ of data recorded by the *BABAR* detector at the PEP-II asymmetric $e^+e^-$ storage ring, represents a significant improvement in precision and is particularly relevant given the recent observations of two new $D_s^+$ meson states [3, 4]. The data have been recorded at and approximately $40\,\text{MeV}$ below the $\Upsilon(4S)$ resonance.

The *BABAR* detector is described in detail elsewhere [5]. Charged particles are detected and their momenta measured by a silicon vertex tracker (SVT) consisting of five layers of double-sided silicon strip sensors and a cylindrical 40-layer drift chamber (DCH), both operating within a $1.5\,\text{T}$ solenoidal magnetic field. Charged particle identification is provided by energy loss measurements in the SVT and DCH and by light recorded in an internally reflecting ring imaging Cherenkov detector (DIRC). Neutral particles are identified and their energies measured by an electromagnetic calorimeter (EMC) composed of 6580 CsI(Tl) crystals.

$D_s^+$ mesons are reconstructed using the decay $D_s^+ \to \phi\pi^+$, $\phi \to K^+K^-$. Kaons are identified by combining the energy deposited in the SVT and DCH with the DIRC information. Tracks not identified as kaons according to the PID criteria are considered as pions.

Our selection criteria are chosen such that the signal significance $S^2/(S + B)$ of the channel $D_s^{*+} \to D_s^+\pi^0$ is maximized. $S$ and $B$ refer to the expected numbers of signal and background events, respectively, which are obtained from a sample of Monte Carlo events.

All combinations of $K^+K^-\pi^+$ candidates have been required to successfully fit to a common vertex; only combinations with a $K^+K^-$ mass within $8\,\text{MeV}/c^2$ from the nominal $\phi$ mass [6] have been retained.

The scaled momentum is defined as $x_p(D_s^+) = p^*(D_s^+)/p_{\max}^*(D_s^+)$, where $p^*(D_s^+)$ is the momentum of the $D_s^+$ candidates in the center-of-mass frame, and $p_{\max}^*(D_s^+) = \sqrt{E_{\text{beam}}^{*\,2} - m(D_s^+)^2}$ is its maximum value. Combinations of $\phi$ and $\pi^+$ candidates are retained if the scaled momentum is 0.6 or greater. Since the kinematics of the $c\bar{c}$ fragmentation process produce charmed mesons with high momenta, this reduces the combinatorial background.

We exploit the longitudinal polarization of the $\phi$ meson to reduce continuum background by requiring that the absolute value of the cosine of the helicity angle $\theta_H$, which is defined as the angle between the $\phi$ momentum direction in the $D_s^+$ rest frame and the momentum direction of one of the kaons in the $\phi$ rest frame, is 0.3 or greater.

The $K^+K^-\pi^+$ invariant mass distribution is shown in Fig. 1. By fitting the sum of a double Gaussian function (to represent the signal) and a third-order polynomial (to represent the background) to this distribution, we find $73\,500 \pm 300$ events. $D_s^+$ candidates are retained if their invariant mass is within $12\,\text{MeV}/c^2$ from the nominal $D_s^+$ mass [6].

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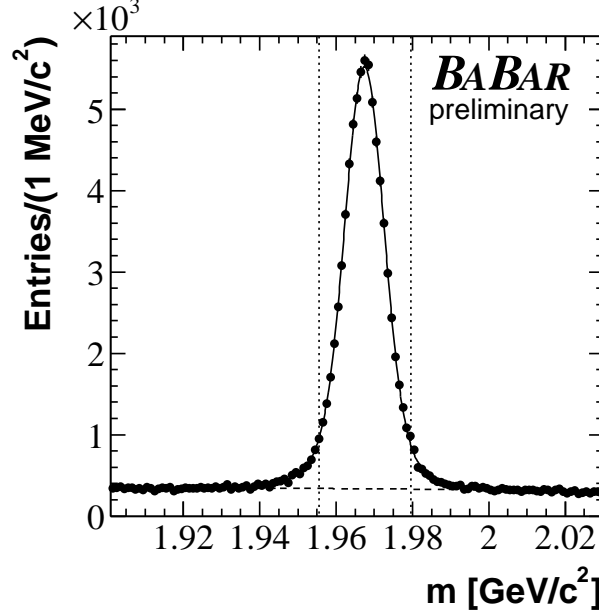[6]Inclusion of the charge conjugated state is assumed throughout this paper.

Figure 1: $K^+K^-\pi^+$ mass distribution. The dots represent data points. The solid line shows the fitted function. The dashed line indicates the portion of the fit associated with the background. $D_s^+$ candidates are selected from the region between the vertical dotted lines.

Each $\pi^0$ candidate is reconstructed by combining two photon candidates. Each photon candidate consists of a calorimeter cluster which is not associated with a charged track and has an energy in the laboratory frame of at least $45\,\mathrm{MeV}$. Additionally, to help remove the background from hadrons, we require the lateral moment [7], which describes the shape of the electromagnetic shower in the calorimeter, to be less than 0.55.

The $\pi^0$ candidates are retained if they have a momentum $p^*$ in the center-of-mass frame greater than $150\,\mathrm{MeV}/c$. Furthermore, the absolute value of the cosine of the decay angle $\theta^*(\pi^0)$, which is defined as the angle between the direction of one of the photons in the $\pi^0$ rest frame and the direction of the $\pi^0$ candidate in the center-of-mass frame, is required to be less than 0.85. For the isotropic $\pi^0$ decay, the $|\cos\theta^*(\pi^0)|$ distribution is flat, while it peaks near 1 for random $\gamma\gamma$ combinations.

Only $\gamma\gamma$ pairs inside a mass window are retained. This window is defined as the region where a function fitted to the $\gamma\gamma$ mass distribution of true $\pi^0 \to \gamma\gamma$ Monte Carlo events exceeds 0.2 its maximum value, which accommodates the asymmetric shape of the $\gamma\gamma$ mass distribution and takes different detector calibrations into account. A kinematic fit is applied to the surviving $\gamma\gamma$ pairs, constrained to the nominal $\pi^0$ mass.

After combining the $D_s^+$ and $\pi^0$ candidates to reconstruct the decay $D_s^{*+} \to D_s^+\pi^0$, we have fitted a function to the mass difference $\Delta m(D_s^+\pi^0) = m(K^+K^-\pi^+\pi^0) - m(K^+K^-\pi^+)$. The function is the sum of a double Gaussian function to represent the signal and

$$f_1(\Delta m) = N \cdot \left(1 - \exp\left(-\frac{\Delta m - m(\pi^0)}{\mu}\right)\right) \cdot \left(\Delta m^2 + a\Delta m + b\right) \tag{1}$$

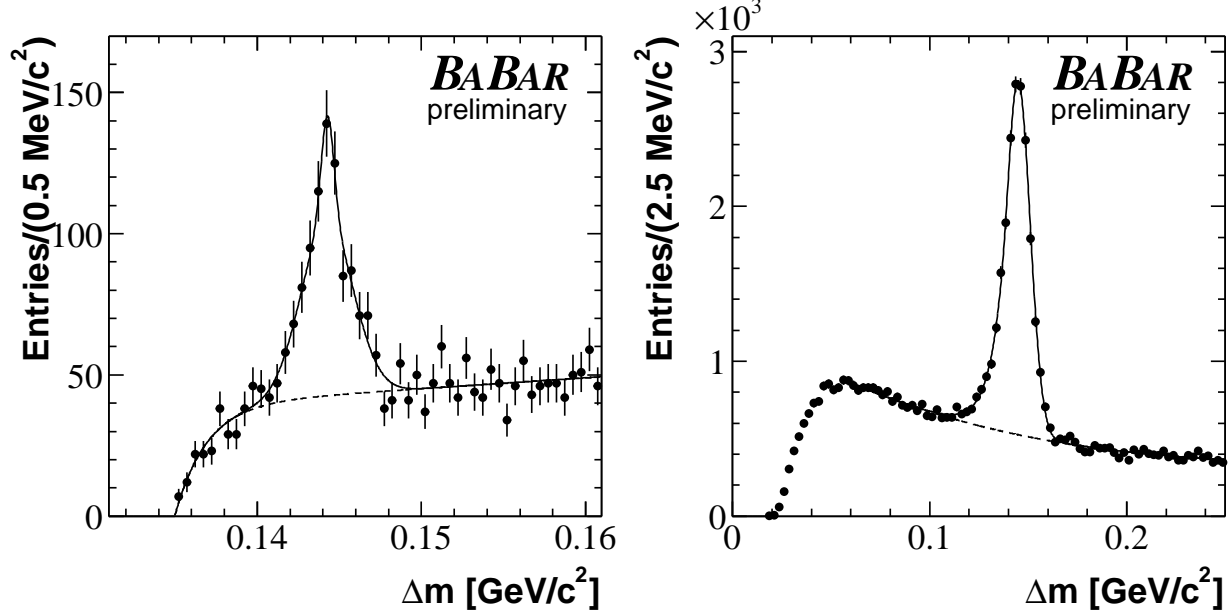(where $m(\pi^0)$ is the $\pi^0$ mass, while $N$, $\mu$, $a$, and $b$ are free fit parameters) to represent the

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Figure 2: $D_s^{*+}$ signals: (a) $m(K^+K^-\pi^+\pi^0) - m(K^+K^-\pi^+)$; (b) $m(K^+K^-\pi^+\gamma) - m(K^+K^-\pi^+)$. The dots represent data points. The solid line shows the fitted function. The dashed line indicates the portion of the fit associated with the background.

background. The exponential term in the background function models the kinematic threshold; it is close to 1 in the signal region.

The result of this fit is shown in Fig. 2(a). We find a signal event yield of $560 \pm 40$.

For the reconstruction of the decay $D_s^{*+} \to D_s^+\gamma$, calorimeter clusters that are not associated with a charged track are considered photon candidates if they fulfill the following requirements. The energy must be 50 MeV or greater in the laboratory frame and 100 MeV or greater in the center-of-mass frame. The lateral moment must be less than 0.8. To reduce the background of photons coming from $\pi^0$ decays, a photon candidate is discarded if it forms a $\pi^0$ candidate with any other photon candidate in the same event. Here, a $\gamma\gamma$ combination is considered a $\pi^0$ candidate if the invariant mass is in the range $115 < m(\gamma\gamma) < 155\,\mathrm{MeV}/c^2$ and has an energy of at least 200 MeV in the center-of-mass frame.

To obtain the $D_s^{*+} \to D_s^+\gamma$ signal event yield, we have fitted a function to the mass difference $\Delta m(D_s^+\gamma) = m(K^+K^-\pi^+\gamma) - m(K^+K^-\pi^+)$. This function is a sum of a "Crystal Ball" function [8]

$$f_2(\Delta m) = N \cdot \begin{cases} A\left(B - \frac{\Delta m - \mu}{\sigma}\right)^{-n} & \text{if } (\Delta m - \mu)/\sigma \leq \alpha \\ \exp\left(-\frac{(\Delta m - \mu)^2}{2\sigma^2}\right) & \text{if } (\Delta m - \mu)/\sigma \geq \alpha \end{cases} \tag{2}$$

(where $N$, $\mu$, $\sigma$, $n$, and $\alpha$ are free fit parameters, and $A$ and $B$ are chosen such that the function and its first derivative are continuous at $(\Delta m - \mu)/\sigma = \alpha$) for the signal, and a third-order polynomial for the background. The fit result is shown in Fig. 2(b). We find $15\,600 \pm 200$ signal events.

To determine the reconstruction efficiencies, two samples of signal Monte Carlo events for the decays $D_s^{*+} \to D_s^+\pi^0$ and $D_s^{*+} \to D_s^+\gamma$, each of which consists of 30 000 events, have been used. The Monte Carlo events have been analyzed using the same procedure as for real data. By calculating the ratio of reconstructed to generated event numbers, we find efficiencies of $\epsilon(D_s^+\pi^0) =$
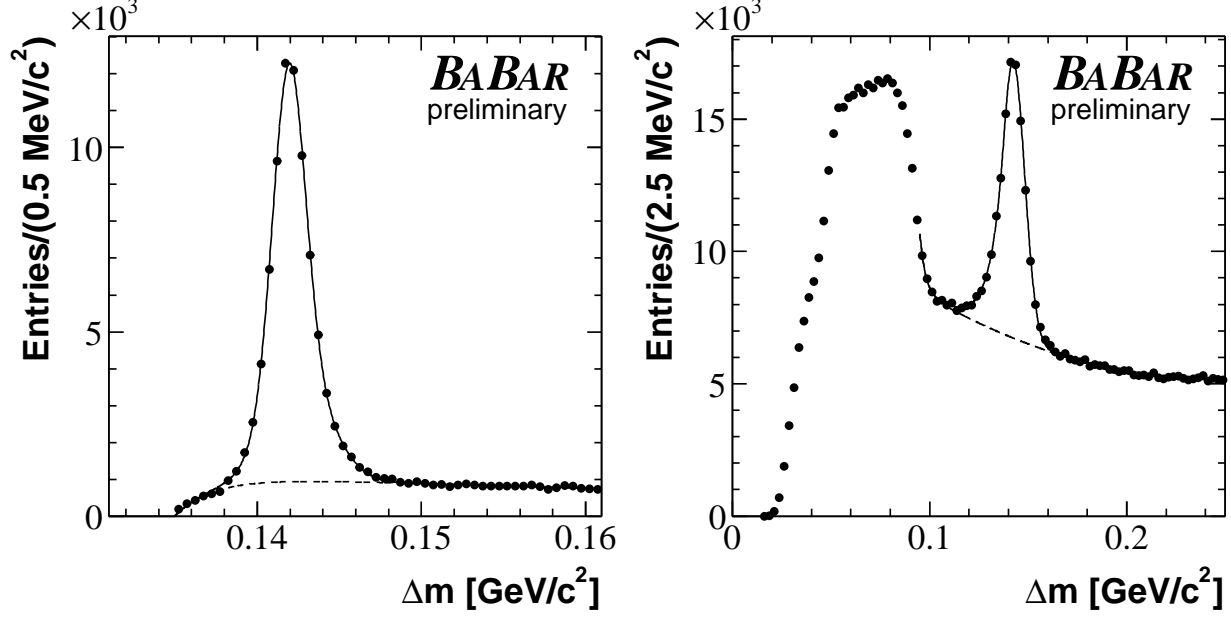
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Figure 3: $D^{*0}$ signals: (a) $m(K^-\pi^+\pi^0) - m(K^-\pi^+)$; (b) $m(K^-\pi^+\gamma) - m(K^-\pi^+)$. The dots represent data points. The solid line shows the fitted function. The dashed line indicates the portion of the fit associated with the background.

$0.041 \pm 0.002$ and $\epsilon(D_s^+\gamma) = 0.071 \pm 0.002$ for the two $D_s^{*+}$ decay modes. The efficiency ratio is $\epsilon(D_s^+\pi^0)/\epsilon(D_s^+\gamma) = 0.58 \pm 0.03$.

For completeness, and as a check of our efficiency calculations, we have also measured the ratio $\Gamma(D^{*0} \to D^0\pi^0)/\Gamma(D^{*0} \to D^0\gamma)$ using the same selection criteria for the $\pi^0$ and photon candidates as in the reconstruction of $D_s^{*+} \to D_s^+\pi^0$ and $D_s^{*+} \to D_s^+\gamma$. To reconstruct the decay $D^0 \to K^-\pi^+$, combinations of $K^-$ and $\pi^+$ candidates are required to successfully fit to a common vertex, and the scaled momentum of the resulting $D^0$ candidate must be 0.6 or greater. Fitting the sum of a double Gaussian function and a third-order polynomial to the resulting $K^-\pi^+$ invariant mass distribution, we find $(996.0 \pm 1.5) \times 10^3$ signal events. $K^-\pi^+$ combinations are retained if their mass differs by less than $17\,\mathrm{MeV}/c^2$ from the nominal $D^0$ mass [6].

The $D^0$ candidates are combined with all $\pi^0$ candidates; the resulting mass difference $\Delta m(D^0\pi^0) = m(K^-\pi^+\pi^0) - m(K^-\pi^+)$ is shown in Fig. 3(a). A fit using a double Gaussian for the signal and the function shown in Eq. 1 for the background yields $69\,000 \pm 400$ signal events.

The $D^0$ candidates are then combined with all photon candidates producing the distribution of the mass difference $\Delta m(D^0\gamma) = m(K^-\pi^+\gamma) - m(K^-\pi^+)$ shown in Fig. 3(b). In this case the signal peak of $D^{*0} \to D^0\gamma$ is close to a large bump due to the reflection of $D^{*0} \to D^0\pi^0$ where one photon comes from a $\pi^0$ decay. We therefore model the background using the function

$$f_3(\Delta m) = N \cdot \left(1 + \exp\left(-\frac{\Delta m - m(\pi^0)}{\mu}\right)\right) \cdot \left(\Delta m^2 + a\Delta m + b\right). \tag{3}$$

(Note that this function is similar to Eq. 1, but differs in the sign of the exponential term.)

The signal is modeled by a "Crystal Ball" function (Eq. 2). The resulting fitted signal consists of $67\,900 \pm 700$ events.

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Table 1: Summary of systematic uncertainties on the branching ratio $\Gamma(D_s^{*+} \to D_s^+ \pi^0)/\Gamma(D_s^{*+} \to D_s^+ \gamma)$.

| | |
|---|---|
| Signal Monte Carlo Statistics | 5.0% |
| Monte Carlo Simulation Uncertainty | 3.6% |
| $D_s^+$ Background | 3.2% |
| $\pi^0$ Background | 3.1% |
| Momentum Dependence | 6.8% |
| Total | 10.2% |

Table 2: Summary of systematic uncertainties on the branching ratio $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma)$.

| | |
|---|---|
| Signal Monte Carlo Statistics | 5.4% |
| Monte Carlo Simulation Uncertainty | 3.8% |
| $D^0$ Background | 0.1% |
| Momentum Dependence | 2.8% |
| Total | 7.2% |

We determine the efficiency ratio by the reconstruction of $30\,000$ signal Monte Carlo events for each of the channels $D^{*0} \to D^0 \pi^0$ and $D^{*0} \to D^0 \gamma$. Efficiencies of $\epsilon(D^0 \pi^0) = 0.037 \pm 0.002$ and $\epsilon(D^0 \gamma) = 0.064 \pm 0.002$, and an efficiency ratio of $\epsilon(D^0 \pi^0)/\epsilon(D^0 \gamma) = 0.58 \pm 0.03$ are found. This is in perfect agreement with the value of $\epsilon(D_s^+ \pi^0)/\epsilon(D_s^+ \gamma) = 0.58 \pm 0.03$. A ratio of $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma) = 1.740 \pm 0.020$ (statistical error only) is obtained, which agrees with the world average of $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma) = 1.625 \pm 0.200$ [6].

Various sources of systematic uncertainties have been studied; they are summarized in Tables 1 and 2.

To verify that the Monte Carlo events model the data correctly, we have studied $\tau$ decays with one or two $\pi^0$ mesons in the final state to obtain energy-dependent Monte Carlo efficiency correction functions for $\pi^0$ mesons and photons. While no correction is necessary, the errors on the correction functions represent uncertainties of the Monte Carlo model and are used as systematic uncertainties.

To test for uncertainties in the background shape of the mass difference distributions, we have considered left and right sidebands in the $D_s^+$, $D^0$, and $\pi^0$ masses. The widths of the sidebands have been chosen such that the number of events in each sideband corresponds to the expected number of background events in the signal region. We have fitted the same functions used to determine the signal yields to the mass difference distributions of the sideband samples. Any discrepancy in the yield between data and Monte Carlo simulation is considered a systematic uncertainty.

We have repeated the measurements of $\Gamma(D_s^{*+} \to D_s^+ \pi^0)/\Gamma(D_s^{*+} \to D_s^+ \gamma)$ and $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma)$ for candidates restricted to bins of $p^*$ (encompassing the range $3 < p^* < 5\,\text{GeV}/c$) by repeating the mass difference fit to the subsample of candidates within each bin. By fitting both a constant function and a first-order polynomial to each branching ratio as a function of $p^*$, we have verified that the measured branching ratios are independent of $p^*$. Nevertheless,

Table 3: Summary of preliminary results. The first errors are statistical, the second represent systematic uncertainties.

| | |
|---|---|
| $\Gamma(D_s^{*+} \to D_s^+ \pi^0)/\Gamma(D_s^{*+} \to D_s^+ \gamma)$ | $0.0621 \pm 0.0049 \pm 0.0063$ |
| $\mathcal{B}(D_s^{*+} \to D_s^+ \pi^0)$ | $0.0585 \pm 0.0043 \pm 0.0056$ |
| $\mathcal{B}(D_s^{*+} \to D_s^+ \gamma)$ | $0.9415 \pm 0.0043 \pm 0.0056$ |
| $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma)$ | $1.740 \ \pm 0.020 \ \pm 0.125$ |
| $\mathcal{B}(D^{*0} \to D^0 \pi^0)$ | $0.6351 \pm 0.0027 \pm 0.0166$ |
| $\mathcal{B}(D^{*0} \to D^0 \gamma)$ | $0.3649 \pm 0.0027 \pm 0.0166$ |

we assume conservatively that the first-order polynomials arise from unknown momentum dependencies of the efficiencies which do not cancel in the branching ratios. Taking the momentum distributions of the $D_s^{*+}$ and $D^{*0}$ mesons into account, we use the difference between the branching ratio represented by the constant function and the first-order polynomial for each distribution as a systematic uncertainty.

The branching ratios are shown in Table 3. By assuming that the $D_s^{*+}$ meson decays only to $D_s^+ \pi^0$ and $D_s^+ \gamma$, i.e. $\mathcal{B}(D_s^{*+} \to D_s^+ \pi^0) + \mathcal{B}(D_s^{*+} \to D_s^+ \gamma) = 1$, and that the $D^{*0}$ meson decays only to $D^0 \pi^0$ and $D^0 \gamma$, i.e. $\mathcal{B}(D^{*0} \to D^0 \pi^0) + \mathcal{B}(D^{*0} \to D^0 \gamma) = 1$, it is possible to calculate the branching fractions, which are also listed in Table 3.

In summary, we have measured a preliminary value for the branching ratio $\Gamma(D_s^{*+} \to D_s^+ \pi^0)/\Gamma(D_s^{*+} \to D_s^+ \gamma) = 0.0621 \pm 0.0049(\text{stat}) \pm 0.0063(\text{syst})$, which is consistent with the previous measurement [2], but has higher precision. We have also measured $\Gamma(D^{*0} \to D^0 \pi^0)/\Gamma(D^{*0} \to D^0 \gamma) = 1.740 \pm 0.020(\text{stat}) \pm 0.125(\text{syst})$, which is more precise than, and in agreement with, the world average [6].

The branching fraction $\mathcal{B}(D_s^{*+} \to D_s^+ \pi^0) = 0.0585 \pm 0.0043(\text{stat}) \pm 0.0056(\text{syst})$ is larger than the theoretical prediction, which is in the $1 - 3\%$ range [1]. However, it should be noted that the theory predicts a strong correlation between $\mathcal{B}(D_s^{*+} \to D_s^+ \pi^0)$ and $\mathcal{B}(D^{*+} \to D^+ \gamma)$; for $\mathcal{B}(D^{*+} \to D^+ \gamma) \lesssim 1\%$, $\mathcal{B}(D_s^{*+} \to D_s^+ \pi^0)$ is expected to be greatly enhanced.

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